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# Landslide risk management in Hong Kong

**Abstract** The combination of dense urban development, hilly terrain, and intense seasonal rainfall has caused acute landslide problems in Hong Kong, which are manifested by a death toll of over 470 people since the late 1940s. Tackling landslide problems in an urban setting, in particular under the effect of climate change, calls for a development and implementation of a holistic risk management strategy. It entails the use of engineering and non-engineering approaches, involving policy, legislative, administrative, innovation, technical, educational, community-based, and emergency-preparedness provisions. In this paper, these two approaches are showcased by the slope safety system that has been developed and promulgated in managing landslide risk for building Hong Kong as a world-class smart city.

**Keywords** Landslide risk · slope safety · climate change · innovation · technology · extreme rainfall

## Introduction

Hong Kong is situated at the south-eastern tip of China. It covers Hong Kong Island, Lantau Island, the Kowloon Peninsula, and the New Territories, including 262 outlying islands. Hong Kong has a mountainous terrain with a scarcity of flat land. Of the total land area of about 1100 km$^2$, about 63% of the land is steeper than 15$^o$ and 30% is steeper than 30$^o$. More than half of the available land area has high to extreme geotechnical limitations to its development potential. As a result, less than 25% of the total land is developed, with the remainder being either country parks or nature reserves. The development over the years has led to the formation of some 60,000 sizeable man-made slopes over the territory of Hong Kong (Fig. 1).

There are two dominant rock types in the urban areas of Hong Kong, namely granitic and volcanic rocks (Sewell & Campbell, 1997). These rocks have been deeply weathered and the depth of weathering could reach locally in excess of 100 m in some cases. The geological conditions are typically highly variable and heterogeneous. Groundwater conditions are also variable both temporally and spatially, in particular groundwater tables could be built up rapidly during heavy rainfall.

The climate of Hong Kong is sub-tropical, with a rainy season from April to October each year. The average annual rainfall is about 2400 mm. Rainfall intensities can be high, with 50 to 100 mm per hour and 250 to 350 mm in 24 hours being not uncommon. According to the Hong Kong Observatory (HKO), the annual rainfall has been increasing progressively at an average rate of 36 mm per decade from 1947 to 2019 as a result of climate change (see the official website of HKO: http://www.hko.gov.hk).

Significant population growth in Hong Kong commenced in the 1950s. Since the early 1950s, the population has increased gradually from less than one million to about 7.5 million by 2019. The rapid population growth and substantial economic expansion have resulted in a high concentration of urban developments on steep terrain in close proximity to man-made slopes and natural hillsides (Fig. 2). Extensive civil engineering and building works were constructed to meet the development needs and thousands of cuts and fills were formed before the late 1970s with inadequate geotechnical engineering input. These potential substandard man-made slopes and natural hillsides are susceptible to landsliding during periods of heavy rainfall. Rain-induced landslides have occurred extensively in Hong Kong over the past century, causing significant socio-economic damage and loss of life (CEDD, 2014). The severity of the landslide problem is manifested by a death toll of over 470 people since 1948. On average, some 300 landslides are reported every year. Landslides in Hong Kong typically comprise shallow failures of less than 3 m in depth with a debris volume of less than 50 m$^3$. Sizeable landslides of several hundred cubic metres or more, many of which involve structure-control failures (i.e. due to adverse geological features and settings), can also occur.

Some notable landslide incidents with multiple fatalities include the 1972 Po Shan landslide, and the 1972 and 1976 Sau Mau Ping fill slope failures (Fig. 3). These landslide disasters culminated in the setting up of the Geotechnical Engineering Office (GEO) (formerly known as the Geotechnical Control Office) in 1977 as a centralized authority to regulate various aspects of slope safety in Hong Kong. Although serious landslides still occur from time to time, the scale and severity of the landslide problem have been reduced considerably as a result of the implementation of a comprehensive slope safety system to manage landslide risk.

Apart from substandard man-made slopes, Hong Kong is faced with the insidious natural terrain landslide hazards posed by the steep terrain, much of which is only marginally stable. For example, a review of aerial photographs taken from 1924 to 2006 has identified more than 100,000 past landslides on natural terrain (MFJV, 2007). In the severe rainstorm of 4 and 5 November 1993, over 800 landslides occurred on the natural terrain on Lantau Island. About 2400 natural terrain landslides occurred in Lantau during another severe rainstorm on 7 June 2008. While most of these natural terrain landslides occurred in relatively remote areas, some of them had affected existing facilities including buildings and roads (Fig. 4). With the growing demand for land to meet housing needs and other purposes, there is a trend to locate developments closer to steep natural hillsides with a consequential increase in landslide risk.

## Challenges in urban environment

Challenges arising from landslides in urban setting of Hong Kong are particularly acute due to the following reasons:

• Landslides in the urban environment of Hong Kong could result in serious consequences due to clustering of developments and high concentration of population and vulnerable facilities.

• Slopes and retaining walls formed in association with urban development, particularly those before the 1970s when geotechnical engineering input was limited, have led to formation of a large number of potential substandard slopes and thereby increase the likelihood of landslide.

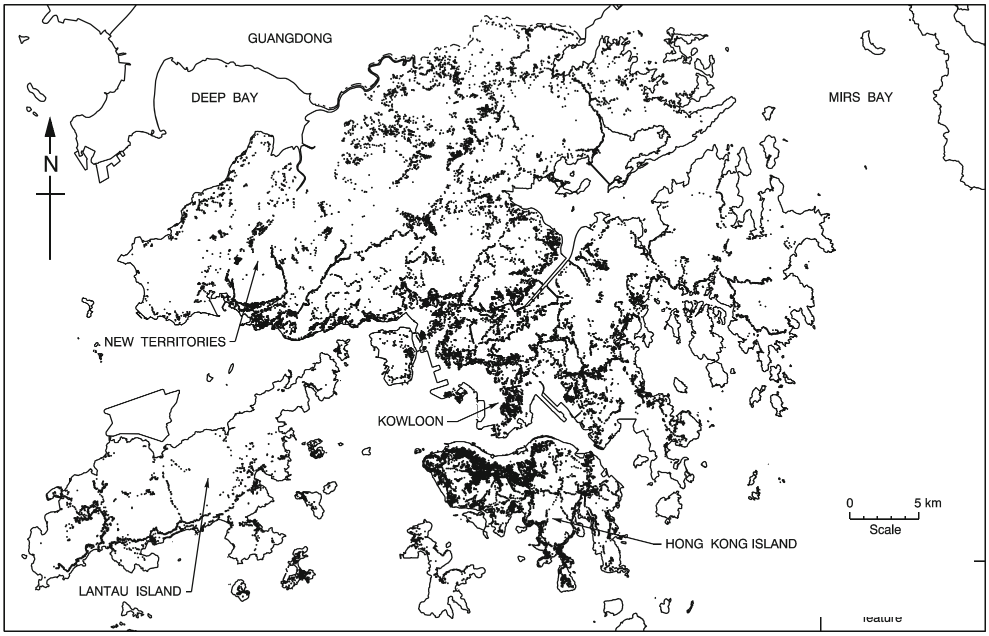



**Fig. 1** Spatial distribution of man-made slopes in Hong Kong

• Given the close proximity of the vulnerable facilities, a relatively small landslide could result in significant impact. Furthermore, the prediction and prevention of such small-scale landslides could be very difficult.

• Landslide problems in urban setting of Hong Kong could be aggravated by human factors, such as localized cutting and filling, concentrated surface water flow, and the possibility of cascading of failures.

• Hong Kong is a highly developed community and there is a shortage of potential developable land, relocation of existing vulnerable facilities is often not viable. Also, provision of landslide prevention and mitigation works can be difficult and costly, given the space and access constraints.

• As a highly developed urbanized city, the public expectation of slope safety is high and the tolerance of landslide fatalities is low. In addition, there are severe environmental constraints in respect of undertaking investigation and engineering works on natural hillsides as the natural environment including endangered plant and animal species may be affected.

• Accompanying the global warming trend and the increase in extreme rainstorm events, the frequency, and scale of landslides are expected to increase correspondingly. This poses additional pressure to the prevailing system in dealing with landslide problem.

**Fig. 2** Development on hilly terrain in Hong Kong

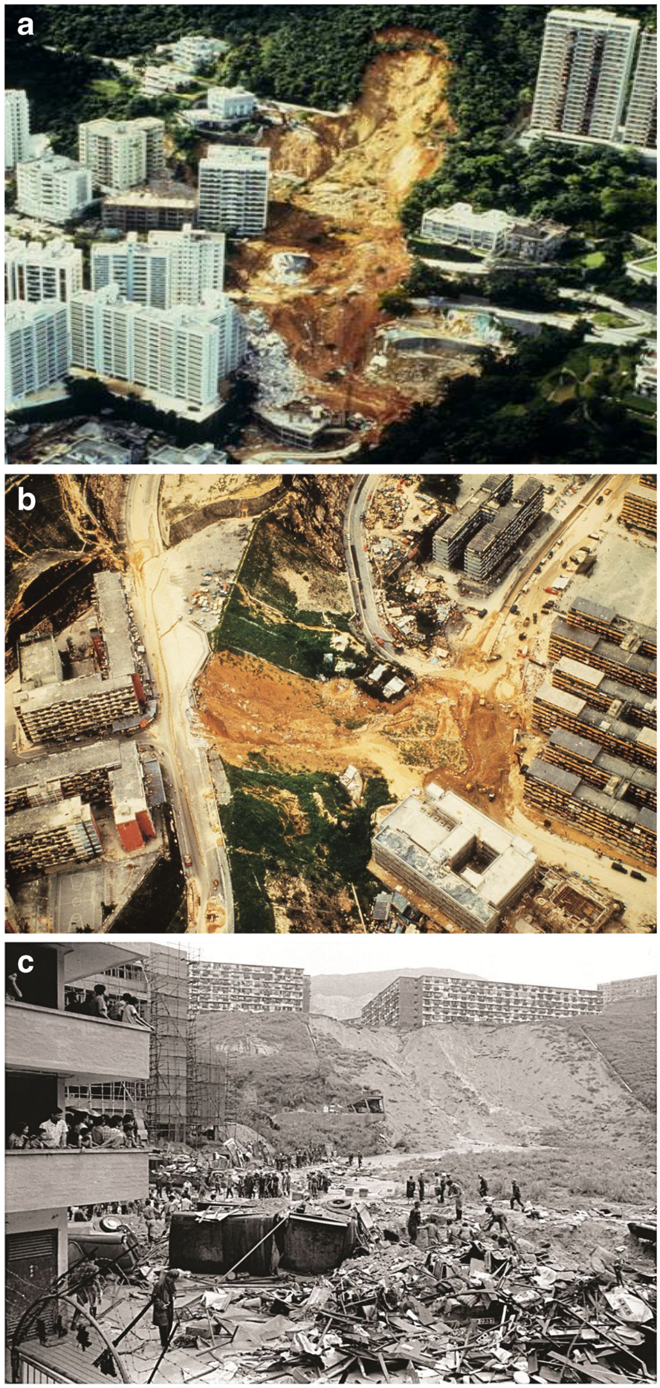


**Fig. 3** The fatal landslides at Po Shan Road and Sau Mau Ping in the 1970s. **a** 1972 Po Shan landslide (a 12-storey building was completely destroyed and the top four storeys of an adjacent building were torn off, causing 67 fatalities). **b** 1972 Sau Mau Ping landslide (debris covered the resettlement area causing 71 fatalities). **c** 1976 Sau Mau Ping landslide (debris poured into lower floors of building causing 18 fatalities)

These challenges are evident in the acute landslide problems faced in Hong Kong, where a holistic strategy for managing urban landslide risk has been developed and effectively implemented through its slope safety system over the past forty years. Hong Kong's experience is described in this paper to illustrate the good practice of managing urban landslide risk in a comprehensive manner.

## The slope safety system in Hong Kong

Before 1977, there was no systematic geotechnical regulation of slope formation. Slopes were basically formed in an empirical manner; many cut slopes were formed at a gradient of about 60°, and fill slopes were formed by dumping or end-tipping without any controlled compaction, at an angle of repose of about 35°. Many of these man-made slopes are potentially substandard and

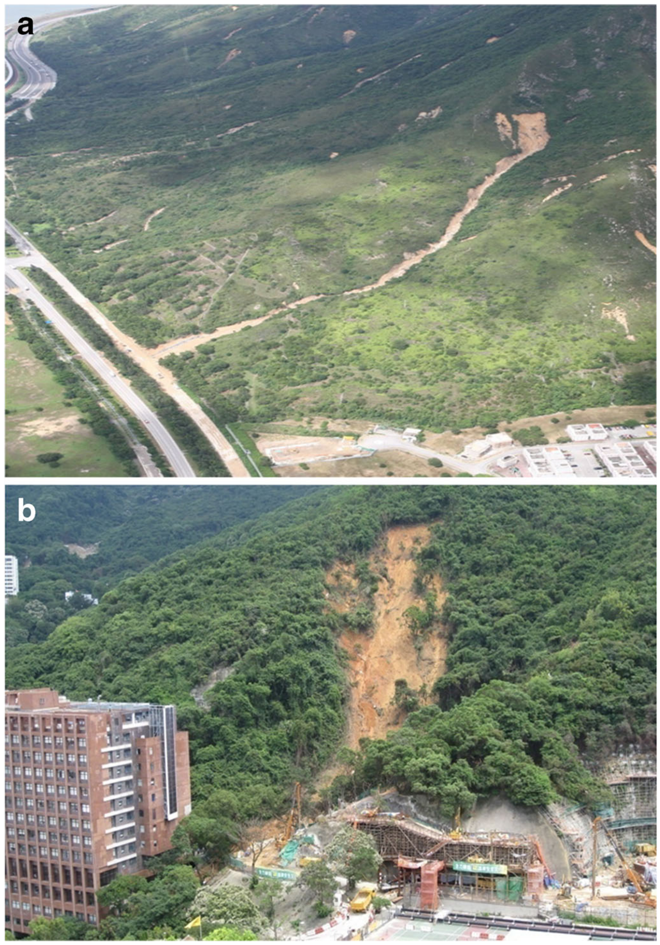



**Fig. 4** Some natural terrain landslides during the severe rainstorm on 7 June 2008. a 2008 landslide at Yu Tung Road, Lantau (major transport corridor to the Hong Kong International Airport was blocked by debris). **b** 2008 landslide at the University of Hong Kong (university facilities were affected)

susceptible to landsliding during heavy rainfall. In the aftermath of the disastrous landslides in the 1970s, the Government established a dedicated specialist geotechnical authority, namely Geotechnical Engineering Office (GEO) in 1977, with an aim to improve the slope safety condition in Hong Kong.

To tackle the challenges, the GEO set out to formulate a slope safety system to manage the landslide risk and regulate slope safety, which incorporates the application of fundamental risk management concepts at the policy administration level. The system has since been subject to progressive improvement over the years. It has now evolved into a comprehensive regime, which embraces a range of initiatives that serve to manage the landslide risk through an explicit risk-based strategy and approach, in a holistic manner.

The primary objectives of the slope safety system are (a) to reduce landslide risk to the community through a policy of priority and partnership, and (b) to address public perception and tolerability of landslide risk in order to avoid unrealistic expectations. The system is primarily a framework for systematic and multi-pronged management of landslide risk. It adds value to the sustainable development of Hong Kong through averting landslide fatalities (i.e. saving lives) and improving the built environment. The holistic slope safety system entails the use of both engineering and non-engineering approaches. As shown in Table 1, there are five key components in the system, namely (a) policing, (b) safety standards and research, (c) specialist works projects, (d) regular slope maintenance, and (e) education and information. In order to deliver the overall policy objectives to meet Hong Kong's needs for the highest standard of slope safety, the GEO has utilized the concept of Key Result Areas (KARs), which covers the main activities of the GEO under the slope safety system as summarized below:

KAR1

Improve slope safety standards, technology, and administrative and regulatory framework

KAR2

Ensure safety standards of new slopes

KAR3

Rectify substandard existing Government slopes

KAR4

Maintain all sizeable Government man-made slopes

KAR5

Ensure that owners of private slopes take responsibility for public safety

KAR6

Promote public awareness, preparedness, and response in respect of landslide risk through public warnings and information services, public education, and publicity campaigns

KAR7

Improve the appearance and aesthetics of slopes

The above framework encapsulates the key components of the slope safety system in a systematic and succinct manner, which helps greatly to convey a clear message to the stakeholders, including the general public, private owners, media, government departments, legislative counsellors, and relevant policy bureau. The background of the development of the slope safety system and the roles of the key components are explained in the following.

| Slope Safety System components | Contribution by each component To reduce landslip risk Hazard | Vulnerability | To address public attitudes |
|---|---|---|---|
| Policing | | | |
| Cataloguing, safety screening, and statutory repair orders for private slopes | ✓ | | |
| Checking both new government and private slope works | ✓ | ✓ | |
| Slope maintenance audit | ✓ | | |
| Inspecting squatter areas and recommending safety clearance | | ✓ | |
| Input to land use planning | ✓ | ✓ | |
| Safety standards and research | ✓ | ✓ | ✓ |
| [e.g. Natural terrain hazard study and mitigation | | | |
| Landslide debris mobility | | | |
| Landslide risk assessment and management | | | |
| Slope greening] | | | |
| Specialist works projects | | | |
| Upgrading existing government man-made slopes | ✓ | | |
| Mitigating natural terrain landslide risk | ✓ | ✓ | |
| Regular slope maintenance | | | |
| Routine and preventive slope maintenance | ✓ | ✓ | |
| Education and information | | | |
| Maintenance campaign | ✓ | | ✓ |
| Personal precautions campaign | | ✓ | ✓ |
| Awareness programme | ✓ | ✓ | ✓ |
| Information services | ✓ | ✓ | ✓ |
| Landslip warning and emergency services | ✓ | ✓ | ✓ |

**Note: Maintenance of registered government man-made slopes and natural terrain defence/stabilisation measures is carried out by the responsible government departments**

## Evolution of slope engineering in Hong Kong

The slope engineering in Hong Kong has evolved with time and it may be classified into three stages:

Stage 1—Empirical slope design before 1977: Slope design and construction were based on rules of thumb, such as 60° steep for soil cut slopes and 35° steep for fill slopes. There was little input from the geotechnical specialists, except for critical facilities such as dams, and there was no centralized authority to exercise a territory-wide geotechnical regulation on these slopes in the course of investigation, design, and construction stages. About 40,000 sizeable man-made slopes were formed in this period, the vast majority of which do not meet the current safety standards, and are vulnerable to landslide at times of heavy rain.

Stage 2—Input from geotechnical specialists to slope design and landslide prevention from 1977 to mid-1990s: In the aftermath of several disastrous landslides (Fig. 3), the GEO was set up in 1977 as the centralized authority to regulate geotechnical engineering and slope safety in Hong Kong. Man-made slopes formed after 1977 in Hong Kong are subject to geotechnical design and checking, to ensure that they meet the required safety standards. The GEO also implemented a Landslip Preventive Measures (LPM) Programme, to systematically assess the stability of the pre-1977 man-made slopes, in accordance with their ranked order of priority, and upgrade substandard Government slopes to the required standards (GCO, 1984). The conventional, deterministic approach

Table 1 Key components of the Hong Kong Slope Safety System

| Slope Safety System components | Contribution by each component | | |
|---|---|---|---|
| | to reduce landslip risk | | to address public attitudes |
| | Hazard | Vulnerability | |
| **Policing** | | | |
| cataloguing, safety screening and statutory repair orders for private slopes | ✓ | | |
| checking both new Government and private slope works | ✓ | ✓ | |
| slope maintenance audit | ✓ | | |
| inspecting squatter areas and recommending safety clearance | | ✓ | |
| input to land use planning | ✓ | ✓ | |
| **Safety standards and research** | ✓ | ✓ | ✓ |
| *[e.g. natural terrain hazard study and mitigation* | | | |
| *landslide debris mobility* | | | |
| *landslide risk assessment and management* | | | |
| *slope greening]* | | | |
| **Specialist works projects** | | | |
| upgrading existing Government man-made slopes | ✓ | | |
| mitigating natural terrain landslide risk | ✓ | ✓ | |
| **Regular slope maintenance** | | | |
| routine and preventive slope maintenance | ✓ | ✓ | |
| **Education and information** | | | |
| maintenance campaign | ✓ | | ✓ |
| personal precautions campaign | | ✓ | ✓ |
| awareness programme | ✓ | ✓ | ✓ |
| information services | ✓ | ✓ | ✓ |
| landslip warning and emergency services | ✓ | ✓ | ✓ |
| Note: Maintenance of registered Government man-made slopes and natural terrain defence/stabilisation measures is carried out by the responsible Government departments. | | | |

of slope stability analysis was adopted in slope design. Landslide prevention was primarily aimed at, and based on, achieving the required design factor of safety (Table 2), although the risk management concept was implicit in the strategy adopted. Risk consideration, if carried out, was made in a qualitative manner.

| Consequence-to-life category | Required minimum factor of safety |
|---|---|
| 1 (e.g. affecting buildings) | 1.4 |
| 2 (e.g. affecting sitting-out areas) | 1.2 |
| 3 (e.g. affecting country parks) | > 1.0 |

Stage 3—Holistic landslide risk management since mid-1990s: In the past 25 years, the GEO has pioneered the development and adoption of an explicit risk-based strategy and approach, in addition to the deterministic approach, for slope stability assessment and landslide risk management. The risk-based methodology embraces a holistic consideration of the likelihood of landslide and its adverse consequences. It can be applied in a qualitative or quantitative framework, with the combined use of both engineering and non-engineering risk management measures, which is now referred to as the Hong Kong Slope Safety System (Chan, 2000). The quantitative applications, in particular, have been instrumental in formulating the overall slope safety strategy for Hong Kong, as well as managing the landslide risk at individual vulnerable sites (Wong, 2005). This approach aligns slope engineering and landslide mitigation with other engineering fields that practise state-of-the-art risk management in an explicit manner.

Table 2 Design standards for man-made slopes in Hong Kong

| Consequence-to-life Category | Required Minimum Factor of Safety |
|---|---|
| 1 (e.g. affecting buildings) | 1.4 |
| 2 (e.g. affecting sitting-out areas) | 1.2 |
| 3 (e.g. affecting country parks) | > 1.0 |

### Landslide risk trend and achievements of the slope safety system

The roles and contributions of the different components of landslide risk management can be illustrated by reference to the landslide risk trend. As noted by Wong (2013), two types of landslide risk trends have been assessed in Hong Kong: (a) historical landslide risk trend and (b) theoretical landslide risk trend.

The annual landslide fatality figures based on documentary records from 1948 to 2019 are shown in Fig. 5. The rolling 15-year average values of the annual fatalities, which better depict the historical risk trend, are also given in Fig. 5.

While historical landslide fatalities reflect the risk that has actually been realized, they do not necessarily represent the 'true' (or theoretical) level of landslide risk, because the historical fatality figures can be affected by the actual rainfall conditions including their spatial distribution and near-miss events. To address this limitation, a quantitative risk assessment (QRA) has been applied in Hong Kong to quantify the levels of theoretical territory-wide landslide risk (Ho & Ko, 2009). The GEO has compiled a comprehensive catalogue of slope, which registers some 60,000 man-made slopes in Hong Kong. The catalogue contains all the essential information of individual slopes, including geographical location, geometry, geology, facilities being affected by the slope, ownership, performance, and stability history (see "Contribution by engineering measures" section under (a) for more details of the catalogue). The overall territory-wide risk of these slopes, in terms of the annual potential loss of life (PLL) that may theoretically be caused by landslides from these slopes, was determined quantitatively (see Cheung & Shiu, 2000 and Cheng & Ko, 2010 for details of the methodology and the overall landslide risk levels of Hong Kong in 2000 and 2010, respectively). Figure 6 is a diagrammatic representation of the overall landslide risk trend, encompassing the historical and theoretical landslide risk in terms of loss of life. Line AB in Fig. 6 shows an increasing trend of landslide risk in the early years, during the era of lack of territory-wide geotechnical regulation by a centralized authority. Rapid urban development after the Second World War with little input from geotechnical specialists resulted in the formation of a considerable number of substandard man-made slopes. This led to the escalation of landslide risk, as reflected by the large number of landslide fatalities at the time. Thus, line AB represents the increasing landslide risk from geotechnically unregulated urban development.

As far as the overall landslide risk is concerned, it was found that (a) implementation of the government's LPM programme has reduced the theoretical landslide risk at year 2000 to about 50% of that which existed in year 1977 (Cheung & Shiu 2000) and (b) by year 2010, the overall landslide risk has been further reduced to about 25% of that in year 1977 (Cheng & Ko, 2010). These are represented by points 'X' and 'E' on the theoretical landslide risk as shown in Fig. 6. It is generally recognized that different components of the landslide risk management have contributed to the reducing risk trend as discussed in the following paragraphs.

### Contribution by regulating and policing new developments

Since the establishment of the centralized authority, GEO, in 1977, territory-wide geotechnical regulation has been enforced to ensure that newly formed slopes in Hong Kong are designed and constructed to the required safety standards. This serves to prevent further increase in landslide risk and thereby freeze the size of the problem. As a result, the increasing risk trend was leveled off (i.e. turned from line BC to line BD in Fig. 6), despite an additional 20,000 sizeable man-made slopes having been formed as a result of urban development in Hong Kong since 1977.

The GEO has implemented a comprehensive geotechnical regulation regime to audit the adequacy of the design and construction of all new geotechnical works including slopes, earth-retaining structures, deep excavations, and tunnels. The geotechnical regulation covers both the Government and private sectors. To empower this regulatory function, legislative amendments, and improvements to administrative instructions have been made (Chan, 1997).

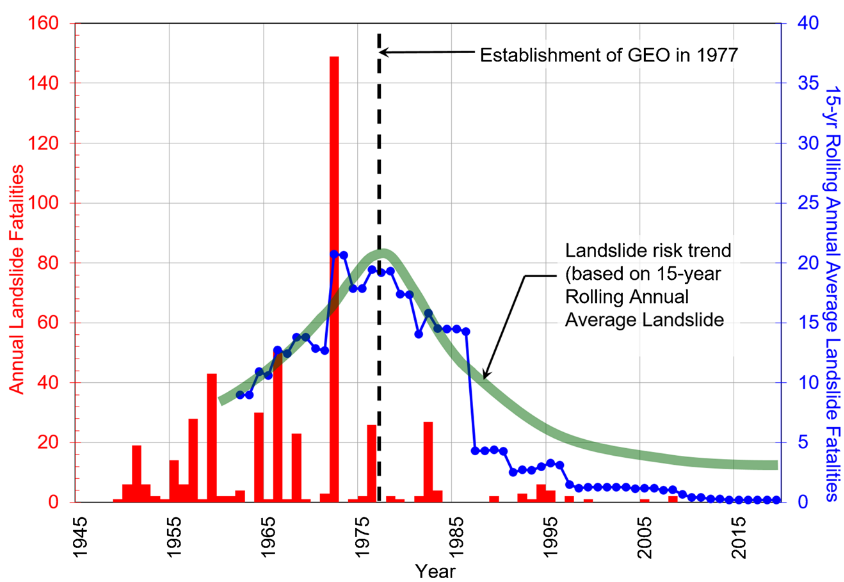



**Fig. 5** Landslide fatalities in Hong Kong (1948–2019)

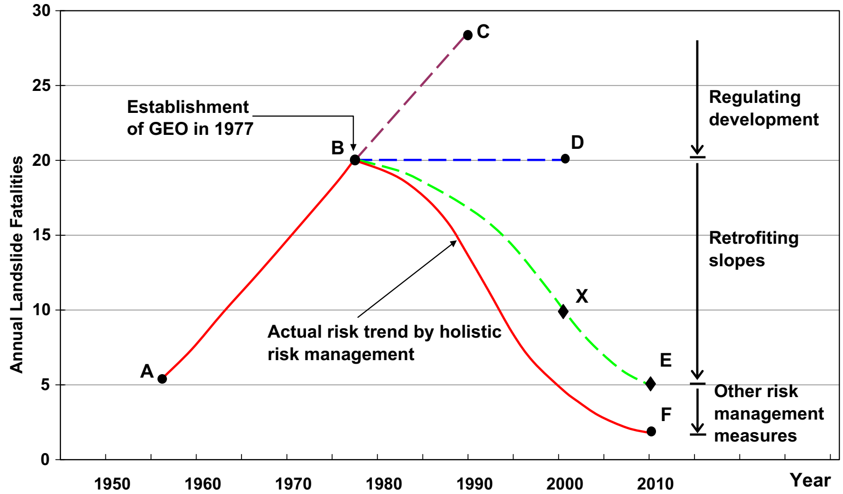



**Fig. 6** Landslide risk trends in Hong Kong. *Note:* Line AB: before enforcing any geotechnical regulation to slope formation in 1977. Line BC: if no enforcement of geotechnical regulation after 1977. Line BD: enforcement of geotechnical regulation after 1977. Line BE: enforcement of geotechnical regulation and retrofitting of substandard slopes after 1977. Line BF: enforcement of geotechnical regulation, retrofitting of substandard slopes, and implementing other non-engineering risk mitigation measures such as landslide warning system and public education after 1977

The geotechnical works of private developments are controlled under the ambit of the Buildings Ordinance (BO) (Chapter 123, Laws of Hong Kong) and its subsidiary regulations. GEO is vested with the responsibility of vetting the geotechnical aspects of works in the private sector. Since 2004, it is a statutory requirement that only qualified geotechnical engineers (i.e. with a license) are eligible for the design of the geotechnical aspects of private building works (which include slope works), in the interest of enhancing the quality of geotechnical input.

The mandate for the geotechnical regulation of public works is derived from administrative instructions issued by the government. Under these instructions, any government departments responsible for public works projects are required to submit the design of their proposed permanent geotechnical works to the GEO for vetting, where this is warranted because of public safety considerations. Construction works shall not be allowed to start unless approval has been obtained from the GEO. The GEO also carries out site audits of the standards of supervision of construction of all new geotechnical works, including slope works. The GEO issues a checking certificate for slopes that are checked to have been designed and constructed to the required standards.

To facilitate the effective execution of geotechnical regulation and landslip preventive works functions, the GEO sets guidelines for slope design and promulgates standard of good geotechnical practice. The GEO publishes and updates technical guidance documents from time to time, based on the findings of the applied research and development work carried out by the GEO and its agents or partners. By 2019, some 400 technical guidance documents, which cover a wide range of geotechnical engineering from slope design, tunneling, excavation and support system to foundation works, have been published and promulgated in the industry. These documents are readily available for viewing and downloading from the GEO's official website (http://www.cedd.gov.hk).

Much of the enhanced slope engineering practice in recent years has originated from an improved understanding of landslides in Hong Kong. The systematic landslide investigation programme of the GEO, which was launched in 1997, has played a key role in advancing the state of knowledge on slope performance and better understanding of the causes and mechanisms of slope failures. This programme also serves as a safety net by identifying slopes that are in need of early attention, as well as providing a basis for auditing the performance of the slope safety system and diagnosing areas for improvement (Ho & Lau, 2010).

#### Contribution by engineering measures

As the prevailing risk posed by the legacy of the pre-1977 old man-made slopes affecting existing developments was at a high level, risk mitigation actions were called for in order to reduce the risk to a more tolerable level. Since the late 1970s, the GEO has embarked on the LPM programme as a systematic, government-funded slope retrofitting initiative, to deal with substandard sizeable man-made slopes registered in the Catalogue of Slopes (please see the "Contribution by engineering measures" section under (a) for more details about the catalogue). Under the LPM programme, man-made slopes formed before the establishment of the GEO are selected for study, in accordance with a risk-based priority ranking system. This system takes account of the relative landslide risk posed to the community. Where high-ranking government slopes are found to be substandard, they would be upgraded to modern safety standards. Where prima facie evidence is established that a private slope is liable to become dangerous, a statutory repair order (known as Dangerous Hillside Order) would be served under the Buildings Ordinance to the private slope owners requiring them to investigate and upgrade their slopes as appropriate within a designated time period.

Before 1994/1995, the annual funding provision for the LPM programme was within US$13 million. In response to increased public demand for slope safety, the funding has increased substantially to about US$115 million per year in the 10-year period between 2000 and 2010, with the annual output targets of the programme set at retrofitting 250 government man-made slopes and carrying out safety-screening studies on another 300 private man-made slopes.

By 2010, all the existing high-risk man-made slopes (i.e. sub-standard pre-1977 slopes affecting buildings and busy roads, which amount to a total of about 7000 slopes) have been retrofitted to the modern safety standard. The cumulative expenditure under the LPM programme has reached about US$1.8 billion. However, there will still be about 33,000 old man-made slopes, which are of lower risk, in the Catalogue of Slopes awaiting assessment and retrofitting.

The outcome of the retrofitting effort is progressive risk reduction along line BE, as illustrated in Fig. 6. The results of QRA confirm that the LPM programme has been cost effective in reducing the potential number of landslide fatalities. The LPM programme is a successful long-term retrofitting project. Two supporting initiatives are instrumental in the effective planning and implementation of the LPM programme. They are:

(a) Compilation of a comprehensive Catalogue of Slopes, under which the geographic extent of all sizeable man-made slopes in Hong Kong (about 60,000 in total) identified from interpretation of historical aerial photographs and field inspections are registered (Lam et al. 1998). The Catalogue of Slopes provides the essential information for assessment of the scale of the problem, risk quantification, determination of slope ownership, planning of the retrofitting studies and works, demarcation of maintenance responsibility, and slope safety management. The catalogue is freely accessible to the public via a web-based Geographic Information System (http://hkss.cedd.gov.hk/hkss).

(b) Development and application of a risk-based priority ranking system (Wong, 2005), for selection of slopes according to their ranked order of priority for study and retrofitting under the LPM programme. This maximizes the rate of risk reduction achieved by the LPM programme. In addition, it provides a rational basis for determining the priority for spending public funds in slope retrofitting, given the relatively small number of man-made slopes that can be dealt with each year under the programme.

Continuous improvements to the slope retrofitting process have been sought over the years (Tang et al., 2007). These include measures to enhance productivity, partnership with practitioners and other stakeholders involved in the project delivery process, slope assessment and stabilization techniques, quality of construction works, slope appearance and integration of slope upgrading and landscaping design (Fig. 7), and environmental performance during construction.

QRA calculations (Cheng & Ko, 2010) suggest that the overall risk posed by natural hillside catchments will be similar to the overall risk associated with the remaining registered man-made slopes upon the completion of the LPM Programme in 2010. The remaining landslide risk posed to existing developments by the year 2010 comes primarily from some 15,000 man-made slopes of moderate risk and about 3000 vulnerable natural hillside catchments with known hazards and that are close to existing buildings and important transport corridors (known as Historical Landslide Catchments).

Through sustained efforts to improve slope safety, the prevailing landslide risk in Hong Kong has been reduced to a reasonably low level, as schematically indicated in Fig. 8. Nonetheless, there is no room for complacency. If investment in slope safety is not maintained, the landslide risk will increase with time due to slope deterioration and encroachment of urban development or redevelopment upon steep natural hillsides. This would cause, in addition to risk to life, significant economic losses and social disruption as a result of road blockages and building evacuation due to landslides, thereby compromising public safety, sustainable development, and Hong Kong's reputation as a modern metropolitan city and tourist hub.

**Fig. 7** Slopes retrofitted under the LPM programme with landscape treatment to enhance aesthetics

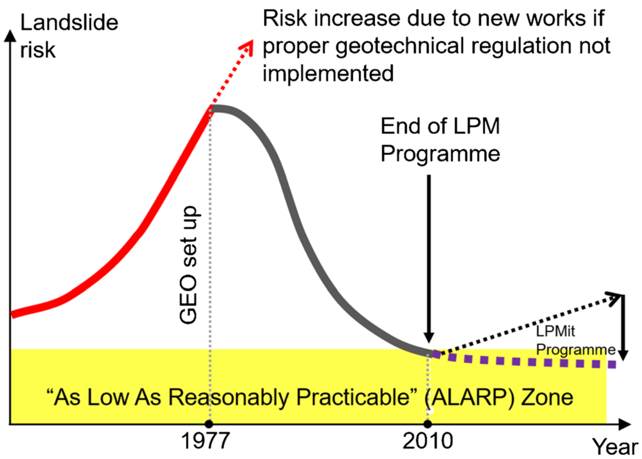



**Fig. 8** Landslide risk profile of Hong Kong

Currently, the remaining major landslide risk comes from some 15,000 man-made slopes of moderate risk affecting development and about 3000 natural hillside catchments with known hazards and are close to existing buildings and important transport corridors. Therefore, the government launched the Landslip Prevention and Mitigation (LPMit) programme since 2010 to dovetail with the LPM programme. The strategy of the LPMit programme is to contain this remaining landslide risk through rolling enhancement of man-made slopes and systematic mitigation of natural terrain landslide risk pursuant to the 'react-to-known hazard' principle, i.e. to carry out studies and mitigation actions where significant hazards become evident. The annual target of the LPMit programme is to complete the upgrading works for 150 substandard government man-made slopes, undertake safety screening studies on 100 private man-made slopes, and carry out landslide risk mitigation works for 30 vulnerable natural hillside catchments from 2010.

#### Contribution by slope maintenance

Regular slope maintenance helps to reduce the chance of shallow landslides caused by increased surface infiltration and wash-out failures caused by concentrated surface water flows, which are common in an urban setting and are aggravated by blockage of surface drainage channels and defective slope surface protection associated with lack of maintenance. As part of the recommended best practice for slope maintenance inspections and works (GEO, 2018), man-made slopes should be inspected by a suitably qualified geotechnical professional at least once every 5 years. This provides a mechanism for detecting signs of distress and deterioration, as well as changes in site setting that may adversely affect slope safety, in order to facilitate taking timely follow-up action. A clear demarcation of the responsibility for slope maintenance is essential to facilitate slope owners to take responsible action. For this purpose, the maintenance responsibility of the 60,000 man-made slopes registered in the Catalogue of Slopes has been established by the Hong Kong Government in the late 1990s. Slopes of government responsibility are assigned to various maintenance departments based on the 'owner maintains' and the 'beneficiary maintains' principles. Privately owned slopes are identified based on the terms of the lease or other land title documents. The information is made available to the public through the Internet.

#### Contribution by non-engineering measures

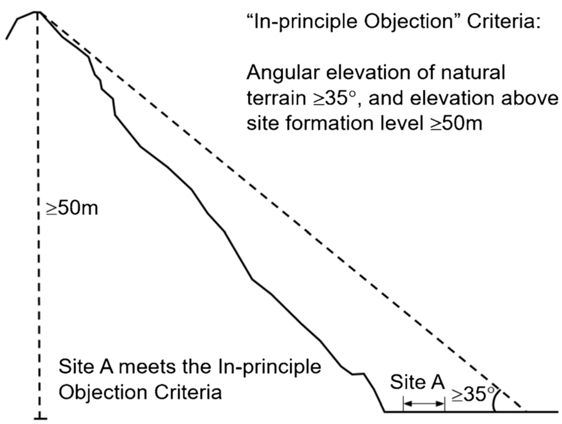
It is evident that the sole reliance on the use of engineering measures to retrofit existing slopes has the following limitations in addressing the landslide problems:

(a) Slope retrofitting works are time- and resource-intensive to implement, and even after many years of effort, there are still a large number of slopes that have not yet reached their turn for upgrading. The risk of these slopes therefore needs to be managed by other means (e.g. by warning system and public education).
(b) Some slopes are particularly difficult to retrofit due to acute access and site constraints, and occasionally due to adverse geological conditions. This renders the use of engineering measures either not practical or not being the preferred risk management strategy.
(c) Landslide problems cannot be solved by the government's action alone. Partnership with the general public and other stakeholders is of the essence in risk management. Partnership in this context has two elements. Firstly, the government's risk management initiatives should meet the needs and expectations of the community. Secondly, the stakeholders, especially the public who are at risk, should play their part in enhancing safety awareness and minimizing their own exposure to landslide risk.>

In view of the above considerations, a suite of non-engineering initiatives has been implemented as part of the landslide risk management in Hong Kong. These include the following initiatives:

(a) Operation of a Landslip Warning system by the GEO to forewarn the public of landslide danger during periods of heavy rainfalls (Yu et al., 2004).
(b) A 24-h landslide emergency service operated by the GEO to advise on emergency and follow-up actions, such as emergency or urgent repair works, building evacuation, or road closure, with a view to addressing the immediate landslide danger.
(c) GEO advises government town planners, land administrators and project departments on land development proposals and land use planning. The purpose is to mitigate landslide risk and facilitate safe and economic development at the earliest possible stage. Special geotechnical conditions may be imposed by the GEO in lease documents for controlling potential landslide hazards. In especially difficult terrain, the GEO may advise against development or make alternative proposals. Administrative measures were introduced in the early 2000s to regulate new developments close to natural hillsides. Various criteria (viz. 'in-principle objection criterion' and 'screening criterion', see Fig. 9 a and b, respectively) were adopted to regulate, as far as possible, the land-use for new developments in areas with significant natural terrain hazards. These also require the study and mitigation of natural

a




b

| Site | Angular elevation of natural terrain ≥20° | Within 50m of ground sloping at >15° | Alert Criteria met? |
|---|---|---|---|
| A | Yes | Yes | Yes |
| B | Yes | No | No |

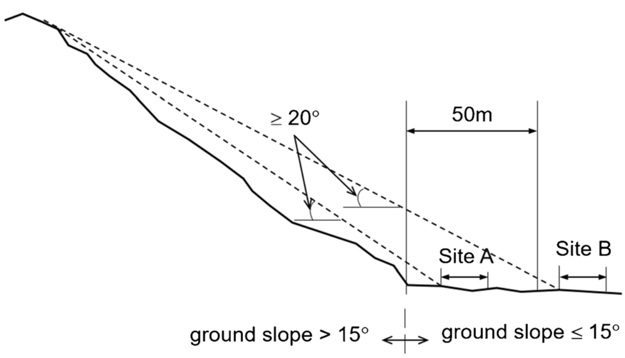



**Fig. 9** Criteria for regulating new developments. **a** In-principle objection criteria for new developments. **b** Screening criteria for assessing the requirement for natural terrain hazard study in new developments

terrain hazards as part of the new developments where necessary.

(d) Provision of slope- and landslide-related information services to the general public and the geotechnical profession, including data on slopes and past landslides, geotechnical and ground investigation reports, rainfall records, and groundwater information. The GEO also operates a Slope Safety Telephone Hotline to provide general information and advice, and mans a community advisory unit to answer queries and give site-specific advice to the public on slope maintenance and rectification of dangerous slopes of private ownership.

(e) Implementation of public education and publicity initiatives, to enhance the public's understanding of the nature and reality of landslide risk, and to promote awareness of taking personal precautionary measures to minimize their exposure to landslide hazard, especially during landslip warning periods (Chan et al., 2007).

(f) Posting of warning signages at selected vulnerable locations.

(g) Providing advice on clearance of vulnerable squatter huts on slope safety grounds (Fig. 10). In 1984, the government launched a systematic programme as part of the Slope Safety System to clear those squatter huts affected by slope instability. When a hut is found vulnerable to landslide risk, the affected occupants will be evacuated and the hut cleared compulsorily. The occupants affected will then be offered rehousing. By 2019, some 80,000 occupants have been rehoused through the programme.

The implementation of the above non-engineering initiatives calls for partnering with the community and stakeholders. This is fostered by openness, transparency, and proactive sharing of information and knowledge, as well as through education. Risk communication is greatly enhanced in the process. This promotes building of trust by the general public in the Government's effort in combating landslide problems and managing landslide risk, and thereby helps to promote tolerability of landslide risk by the community at a more rational and realistic level.

The non-engineering initiatives form an integral part of landslide risk management. Their contributions are shown diagrammatically as line BF in Fig. 6, reflecting a further reduction in the landslide risk from the theoretical level (line BE) that accounts only for the effect of slope retrofitting works.

Over the past 40 years, the actual annual landslide fatalities in Hong Kong have been consistently less than the theoretical risk level by at least 50%. While the risk figures should only be taken as an indication of the likely order of landslide risk, the overall risk trend suggests that the contribution of the non-engineering initiatives to reduction of landslide risk in Hong Kong could be fairly significant.

## Facing the future challenges

### Extreme rainfall associated with climate change

Global and regional climates are changing as a result of increasing greenhouse gas concentrations in the atmosphere. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) has rigorously assessed the current and future states of the climate system and re-affirmed the unequivocal warming of the Earth's climate system and concluded that many changes observed since the 1950s were unprecedented over decades to millennia. AR5 also delivered a clear consensus reached by climate scientists worldwide that climate change was induced by human activities.

It is evident that a warming climate could bring more frequent and strong tropical cyclones to certain regions, and the associated rainfall is likely to increase. Such effects have been emerging in recent decades, and Hong Kong is not immune to the clear and present danger brought by climate change as well as its long-term impact in the future. For example, the June 2008 extreme rainfall event, with a return period of about 1,000 years, caused more than 3000 landslides on both man-made slopes and natural terrain in Hong Kong.

Extreme rainfall events have become more frequent in Hong Kong. While it used to take several decades to break the record in the past, the hourly rainfall record at the Hong Kong Observatory (HKO) headquarters was broken quite a few times in the past

**Fig. 10** Vulnerable squatter huts on sloping ground

several decades, and the latest by a significant margin (see the frequency and magnitude of rainfall breaking records before and after the 1990s in Fig. 11). The HKO has conducted a sophisticated analysis of the rainfall data and the results indicate that the chance of hourly rainfall of 100 mm or more has doubled over the past century (Wong et al., 2011).

The GEO, in collaboration with scientists and meteorologists in the HKO, have reviewed various credible climate change scenarios, with particular reference to rainfall. Indeed, estimating the impact of climate change on the rainfall of Hong Kong is a challenging task. Gaps still exist between the best estimates of the future climate projection in the regional- to city-scale and practical applications based on these estimates. For better projections of the future rainfall characteristics, especially regarding extreme values, three possible approaches are considered technically feasible (Chan & Tam, 2012):

(a) Projection of trend—The future climate may be extrapolated based on the observed trends from historical records. This can be carried out using extreme value statistics, with minimal computational costs. However, the assumption that the future extreme event frequency follows the observed trends may not be valid, and there are no physical principles behind the assumption.

(b) Statistical downscaling of Atmosphere-Ocean General Circulation Models (AOGCM) projections—This is an empirical approach to downscale coarse-scale climate projection to that pertaining to a specific location in Hong Kong. Although the approach is not computationally demanding, it is not

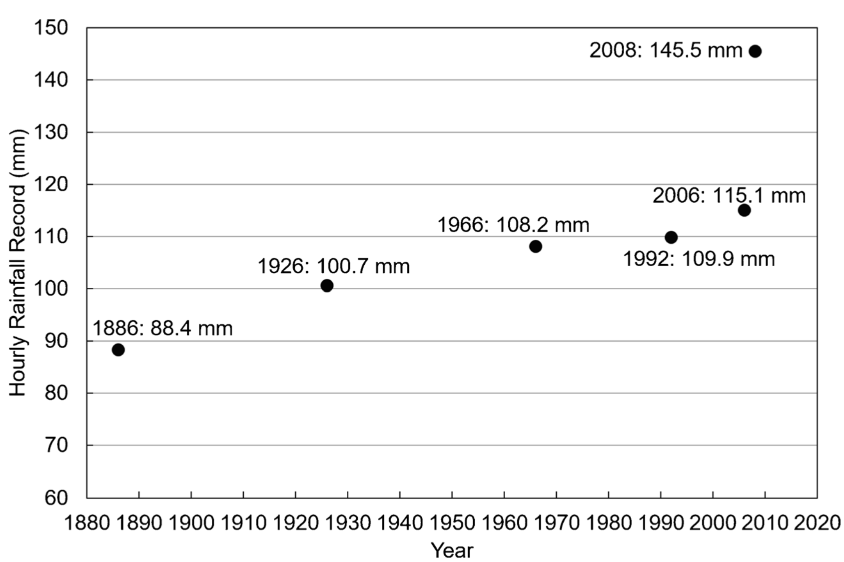



**Fig. 11** Record-breaking hourly rainfall events at the Hong Kong Observatory headquarters (1885–2019)

physics-based and hence, it may not capture completely the physics governing changes of extreme rainfall under global warming.

(c) Dynamical downscaling of AOGCM projections—This method is physics-based and its results are dynamically consistent. However, it is computationally very demanding. AOGCM climate projections of high temporal resolution (say, at least at 6-hour intervals) as an input for the analysis have to be obtained from relevant modeling centres directly.>

In 2016, the HKO carried out a statistical downscaling study on extreme rainfall projection for Hong Kong in the twenty-first century using the Coupled Model Intercomparison Projection Phase 5 (CMIP5) which had a typical resolution of 200 × 200 km (Chan et al., 2016). The results suggest that there would be generally more extreme rainfall days and the increase is more prominent in the late twenty-first century. In addition, both the annual maximum daily rainfall and the annual maximum 3-day rainfall are expected to increase.

Probable maximum precipitation (PMP) is a widely used concept in civil engineering. It is defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year (WMO, 2009). The 4-h and 24-h PMP for Hong Kong were established by the HKO in the late 1990s (HKO, 1999). AECOM and Lin (2015) and Lin (2017) reviewed the PMP estimates for Hong Kong and updated the 4-h and 24-h PMP estimates using maximization and storm transposition methods with storm transposition and orographic adjustments. As indicated in Fig. 12, the PMP updates are higher than the extreme rainfall records in Hong Kong to some noticeable extent and higher than the rainfall records in Southeast China and Taiwan, and very close to the envelop of the world records.

In early August 2009, the devastating Typhoon Morakot brought Taiwan the maximum recorded rainfall in over the last 50 years of 2965 mm in 4 days, which also approached the world record for this duration. This huge amount of rainfall has caused numerous severe landslides and flooding throughout the southern part of Taiwan. One massive landslide devastated the entire Shiaolin village, killing more than 500 people in a single incident. The HKO employed a numerical model (viz. Advanced Research Weather Research and Forecast (WRF) model) to conduct a simulation of the amount of rainfall that would fall if a typhoon with strength of Typhoon Morakot was to centre over Hong Kong. The results indicate that the transposition of the rainstorm associated with Typhoon Morakot to Hong Kong could result in 24-h rainfall corresponding to 87 to 110% of the PMP for an area of 900 km$^2$ (i.e. ranging from about 520 to 660 mm). This provides a useful indicator to GEO for enhancing the prevailing emergency preparedness as part of the landslide risk management.

### Emergency preparedness

Under the GEO's emergency preparedness and response system to landslides, standby teams of geotechnical professionals are to inspect landslides and make expert advice on the necessary risk management actions to deal with immediate and obvious landslide danger in order to safeguard public safety. The adequacy of the prevailing emergency preparedness and response, together with the crisis management plan, has been reviewed following the severe 7 June 2008 rainstorm in Hong Kong as well as the rainfall brought by Typhoon Morakot in Taiwan. The update of PMP as noted previously (AECOM & Lin, 2015; Lin, 2017) also contributed to this review.

The rainstorm of 7 June 2008 in Lantau was about 60% of the PMP estimate for Hong Kong. The impact of a more severe or an extreme rainstorm could be more serious. To gain an understanding of the potential landslide impact of an extreme rainstorm, a

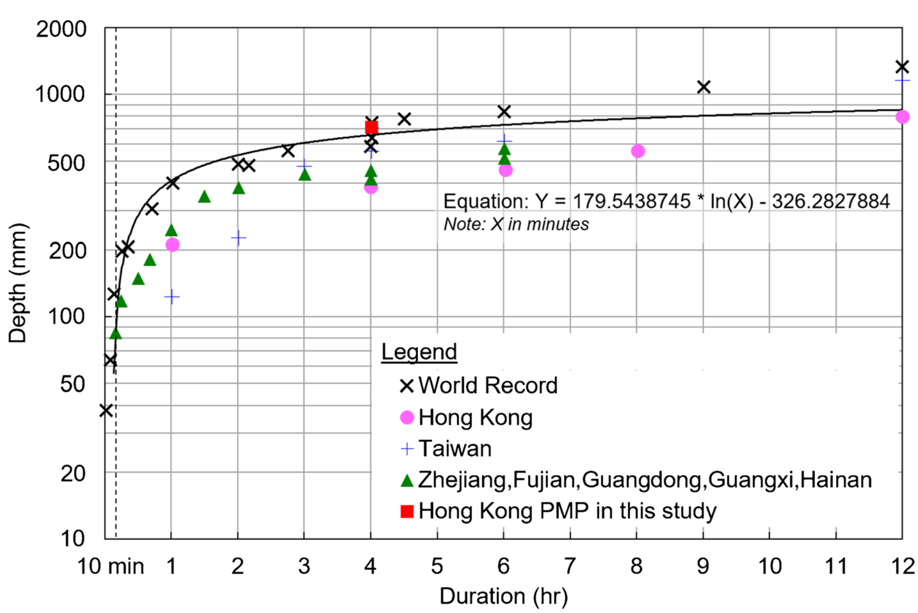



**Fig. 12** Comparison of Hong Kong PMP Updates with Extreme Rainfall Records in Hong Kong, Taiwan, Southeast China, and the World Records (Lin, 2017)

landslide impact assessment has been carried out using the 7 June 2008 rainstorm at Lantau as a starting point and assuming that it hits Hong Kong Island. The results indicate that about 2000 natural terrain landslides could occur on Hong Kong Island, about 200 to 300 of which could affect roads and buildings. The findings of the assessment help to enhance the current emergency system.

Landslip warning system operated by the GEO is a key component of the emergency preparedness, which forewarns the public of landslide danger during periods of heavy rainfalls. The prevailing Landslip Warning criteria are based on a threshold number of predicted landslides on man-made slopes based on the correlation of 24-h rainfall and landslides reported to the government. Past studies by the GEO (Ko, 2005) showed that the natural terrain landslide density tends to increase drastically with an increase in normalized rolling 24-h rainfall, which means that very widespread natural terrain landslides can occur during intense rainfalls. The GEO sees the need to develop separate natural terrain landslip alert criteria. These are to supplement the prevailing Landslip Warning provisions for enhanced emergency preparedness and response.

The new natural terrain landslip alert criteria are intended to supplement the prevailing algorithms for issuing and cancelling landslide warning. The formulation of the new alert criteria involves deriving storm-based landslide density from the year-based landslide density using statistical methods, with due consideration given to both 4-h and 24-h rainfall. A calibration exercise was carried out with the use of all the recorded severe rainfall events since 1985, which confirmed that the newly proposed alert criteria are pragmatic and appropriate. As a result, a 3-tier natural terrain landslip alert framework has been developed as in Table 3. The alert levels are to be determined on the basis of the actual recorded rainfall and an equivalent number of natural terrain landslides predicted using the rainfall-landslide correlation. This accounts for the relative hazard levels of different regions because of the differing settings, such as urban, urban fringe, or rural settings, by means of suitable scaling factors derived empirically from past landslide events. For the time being, the new alert criteria for natural terrain landslides are being operated as internal alerts for reference by Government emergency managers. In contrast, the prevailing Landslip Warning system is broadcast to the general public via television and radio. When large numbers of natural terrain landslides are predicted, the new arrangement is to mobilize special standby emergency teams comprising professionals with requisite engineering geological expertise to inspect the natural terrain landslides and assess the residual risks

**Table 3** The 3-tier natural terrain landslip alert framework

| No. of predicted natural terrain landslides | Alert level | Scenario |
|---|---|---|
| ≥ 500 to < 1000 | 1 | Alert of possible widespread natural terrain landslides |
| ≥ 1000 to < 2000 | 2 | Warning of widespread natural terrain landslides |
| ≥ 2000 | 3 | Warning of very widespread natural terrain landslides |

**Innovation and technology**

As the central body responsible for managing landslide risk in Hong Kong, GEO always looks for initiatives to promote and apply innovation and new technologies to enhance its services. In 2018, the GEO formulated a long-term strategy on the application of innovation and technology (I&T) in landslide risk management. In formulating the strategy for I&T, four core areas, namely (i) automation and robotics, (ii) digital technology, (iii) artificial intelligence (AI), and (iv) novel technology, have been grouped according to the nature and potential applications of the technologies (Fig. 13). To date, some ten new technologies that have potentials for wide application in the slope safety system have been identified. Examples of these technologies are given in the following paragraphs.

Artificial intelligence (AI)—AI and deep learning have proven to be useful in many applications. The GEO has collaborated with industry partners and academia to explore the use of artificial intelligence and deep learning in landslide risk management. As a start, GEO has initiated two pilot studies to explore the applications of artificial intelligence in slope safety management, including the identification of rock outcrops on natural hillsides throughout Hong Kong and identification of natural terrain landslides from digital aerial photographs.

The first pilot study aims to explore the potential of using deep machine learning to analyse remote sensing data to identify areas with rock exposure on natural terrain throughout Hong Kong in an efficient manner. It serves as the first attempt to use Image AI in engineering geological mapping in Hong Kong. The results will be useful in enhancing the landslide susceptibility analysis for natural terrain in Hong Kong.

The second study is to develop a computerized algorithm with machine learning capability which allows automatic and systematic identification of natural terrain landslides from digital aerial photographs. Currently, the trained AI model is applied to several sites of different geology and landslide patterns. By using AI and machine learning technique, the natural terrain landslides could be identified automatically and timely, which helps to speed up the process of updating the territory-wide landslide dataset.

Traditionally, the correlation between rainfall and landsliding is established using statistical techniques. Given the highly non-linear nature of the rainfall-landslide correlation and the various sources of uncertainties involved, the GEO is exploring the potential of using AI and deep learning technique in this area with a view to enhance the landslip warning system as described above.

Mobile robot—In recent years, there have been many advancements in the development of autonomous mobile robots that are designed to carry out many repetitive tasks and access dangerous places (Fig. 14). One of the key roles of the GEO is to inspect landslides and provide expert advice to deal with immediate and obvious landslide danger to safeguard public safety. The GEO is exploring the potential of using mobile robots that could traverse rough terrain for inspection of landslide sites.

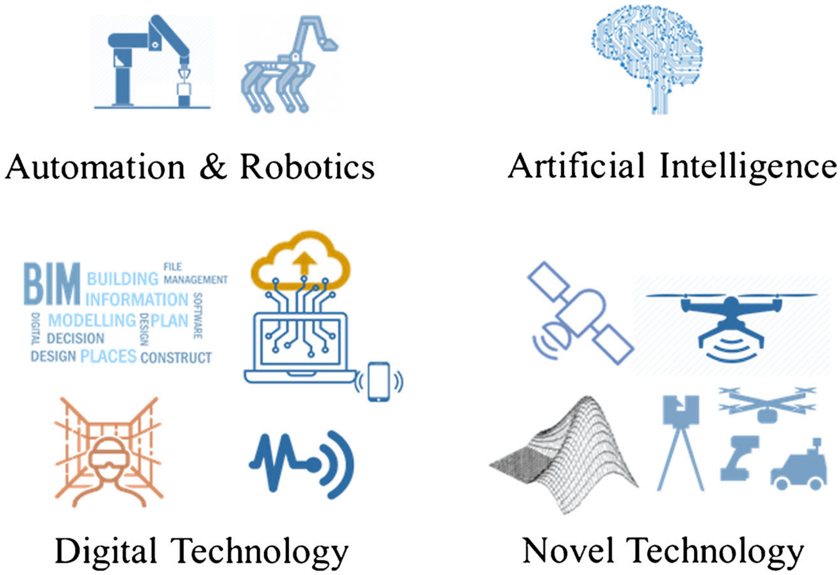



**Fig. 13** Four core areas under I&T strategy

The robots could also be equipped with articulating arms and sensing camera, which facilitate and enhance the efficiency and effectiveness of the inspection and rescue process.

Remote sensing technology—The GEO has been using a new generation of handheld laser scanning (HLS) equipment, which could be operated in difficult terrains, to acquire the land topography with high accuracy. The HLS has been applied for various landslide-related tasks, including emergency inspection of landslide scars, mapping of natural terrain, rock joint mapping, etc. Site trials are being conducted to establish the accuracy of the data collected and develop methods to efficiently cleanse the data for future applications.
Virtual reality and immersive reality—Simulations using virtual reality (VR) and immersive reality (IR) help to engage stakeholders by providing a unique environment and experience to the users. As part of the public education efforts to promote slope safety awareness to the public, the GEO has produced a few VR simulations on the experience of surviving past landslides at Po Shan and Sau Mau Ping in 1972 (Fig. 3). These first-hand simulations proved to be very popular in exhibitions organized by the GEO. In addition, the GEO collaborates with the Hong Kong Jockey Club Disaster Preparedness and Response Institute in producing VR training kits to simulate scenarios of inspecting professionals attending landslide inspections. The training simulations are scenario based, which mimic role play games where actions and activities are driven by the decision made by the trainee at individual steps. These aim to enhance the preparedness of the inspecting professionals in dealing with different situations during landslide inspections. The GEO is also exploring the opportunities of using VR and IR in the practice. For example, the digitization of engineering

**Fig. 14** Autonomous mobile robot

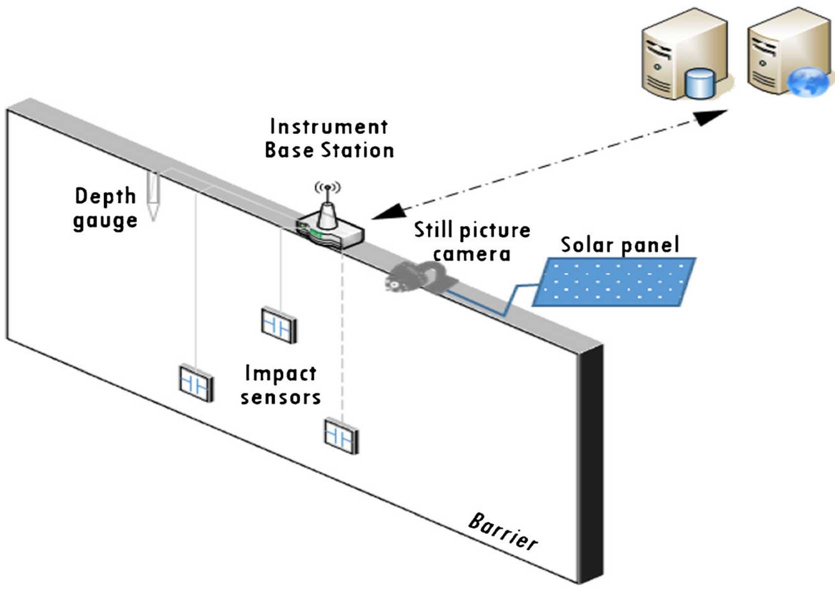



**Fig. 15** Smart barrier with LDS

design using Building Information Modelling (BIM) produces VR and IR simulations that could help identifying potential construction problems in the early stage of a design, as well as communicating with relevant stakeholders of the project intent and the as-built environment.

Landslide detecting system (LDS)—Landslide debris-resisting barriers are commonly adopted in Hong Kong for mitigating natural terrain landslide risks. They are designed to withstand severe rainfall scenarios according to past records. In case of unprecedented extreme rainfall scenarios, they may be overwhelmed. It takes swift emergency responses before worsening of the scenarios. The swift responses rely on timely reporting of landslide debris impacts on the barriers, but debris intercepted by the barriers is difficult to observe due to inaccessibility and obstructed visibility on natural hillsides. Recently, the GEO has developed a Landslide Detecting System (LDS) with the aid of Internet of Things (IoT) that could alert the GEO in a timely manner when landslide debris hit the debris-resisting barriers (Fig. 15). The system is sensor-based and is being tested at some trial sites with different settings. Once the reliability of the system is established, all the debris-resisting barriers will be equipped with the system, and become smart barriers. This will enhance the landslide emergency service provided by the GEO.

Common operation picture (COP)—Situation awareness and efficient communication are essential to emergency management. The GEO is developing a 'common operational picture (COP)' which provides a new map-based common information technology (IT) platform with Geographic Information System (GIS) functions for sharing real-time emergency and impact information such as landslides, flooding, and major road incidents among various bureau and departments in the government (Fig. 16). It also incorporates related information such as weather conditions and status of temporary shelters to provide a comprehensive platform for emergency responses.

COP could enhance the common situational awareness of the emergency managers in relevant bureaux and departments and facilitate them to make effective, consistent, and timely decisions and mobilize resources. It also strengthens coordination and enhances planning and responsiveness to emergency situations in a holistic manner. This enables frontline staff and emergency managers to view the emergency information anytime and anywhere via desktop workstation and mobile devices. With COP, it is envisaged that the efficiency and effectiveness of the emergency service and the crisis management could be much enhanced.

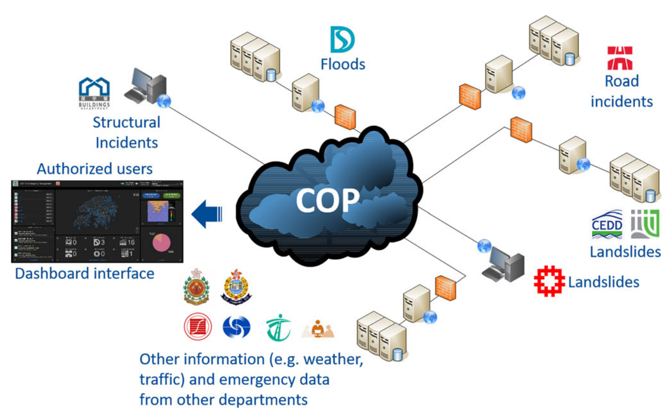



**Fig. 16** Common operating platform for sharing real-time emergency information

## Conclusions

Experience in Hong Kong has emphasized the importance of a holistic landslide risk management strategy and the continuous improvement culture. This has been cultivated by the GEO that contributed to many innovations, and significant technical and non-technical advances in the landslide emergency preparedness and crisis management for extreme weather. The slope safety system in Hong Kong has been implementing and evolving continuously, which can be best summarized by the following key elements and objectives:

- Policing by a centralised authority to make sure that all the new slopes are designed and constructed to the required safety standards.
- Carrying out applied research and development to facilitate standards and guidance setting.
- Setting geotechnical standards and guidance to unify the safety requirement.
- Carrying out specialist works projects to upgrade substandard slopes.
- Carrying out regular slope maintenance to maintain sustainability of safety level.
- Providing landslide warning system and the corresponding emergency service to the general public.
- Providing information and education to raise the slope safety awareness of the general public.
- Adopting innovation and novel technology to enhance continuous improvement of the system.

The concerted effort of the GEO and all stakeholders in the community of Hong Kong over the past four decades has brought about substantial reduction in landslide fatalities. Despite the achievements made with regard to landslide risk reduction, there is no room for complacency. It is pertinent that all stakeholders should remain vigilant about landslide risk. An acute and upcoming challenge is the potential climate change impact and the associated extreme rainfall. This was highlighted by the landslide devastation caused by the severe rainstorm of 7 June 2008 in Hong Kong, which was the most intense rainstorm since rainfall records began in 1884.

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